

# MICE Spectrometer Solenoid 2B Issues

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The MICE Solenoid 2B review was requested by the FNAL Directorate because of several magnet system failures during tests at the vendor site. This report is based on findings during a visit to WANG NMR (See Appendix), discussions at LBNL, and MICE Notes [1] –[12]. The report is related to the possible failure scenarios and concentrates on the electromagnetic nature of these issues. In general there were two types of failures:

- Burned HTS current lead (See Fig. 1) at 238 A current and 81K leads temperature [11].
- Coil M2 open circuit after the 257 A quench.

Regarding the first item above, after modifications the solenoid 2B was successfully cooled down to 4.5 K, the helium vessel filled with LHe, and HTS leads were operated at reasonable temperature, 50 K. Nevertheless, additional losses during quench could overheat HTS current leads, and busses. These areas should be properly modeled and investigated to avoid potential future HTS lead failures.



Fig. 1 Magnet 2 burned out HTS lead.

## 1. Solenoid Magnetic Field

The spectrometer solenoid consists of 5 superconducting coils (See Fig.2): matching coils M1, M2, end coils E1, E2, and the central coil C. The coils were wound on an Al 6061-T6 mandrel using a single strand of NbTi superconductor with outer dimensions 1.0 mm x 1.6 mm, Cu:Sc

ratio 3.5, and a critical current  $>760$  A at 4.2 K and 5 T magnetic field. The cold mass is mounted inside a LHe vessel.

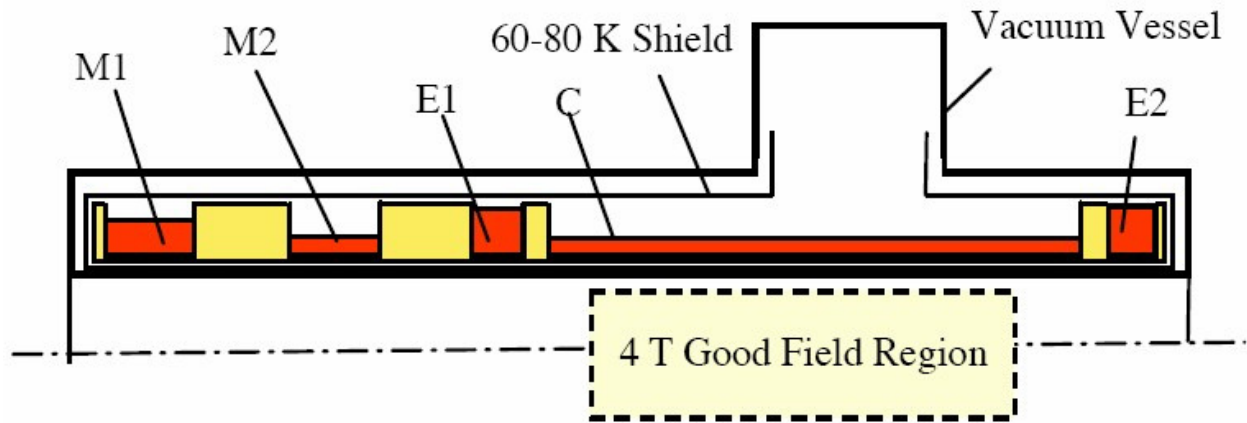


Fig. 2 Spectrometer Solenoid cross-section.

All coils, M1-M2-E1-C-E2, during tests were connected in series and powered from a single 300 A current main power supply (See Fig. 3, right). The magnetic field distribution at this DC current was checked using the OPERA2D code.

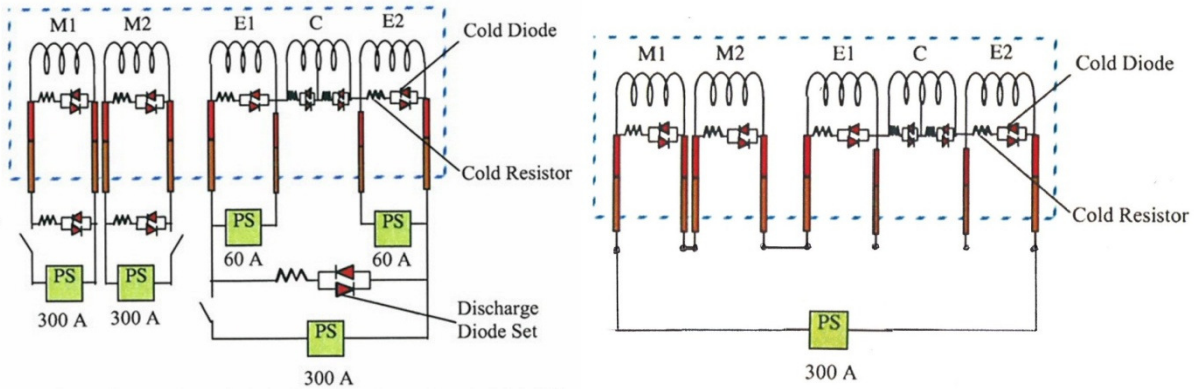


Fig. 3 Solenoid electrical circuit schemes: original (left), 2B test (right).

The model geometry and the flux density in the coils at 257 A is shown in Fig. 4, Fig. 5, and in the area of HTS current leads in Fig. 6.

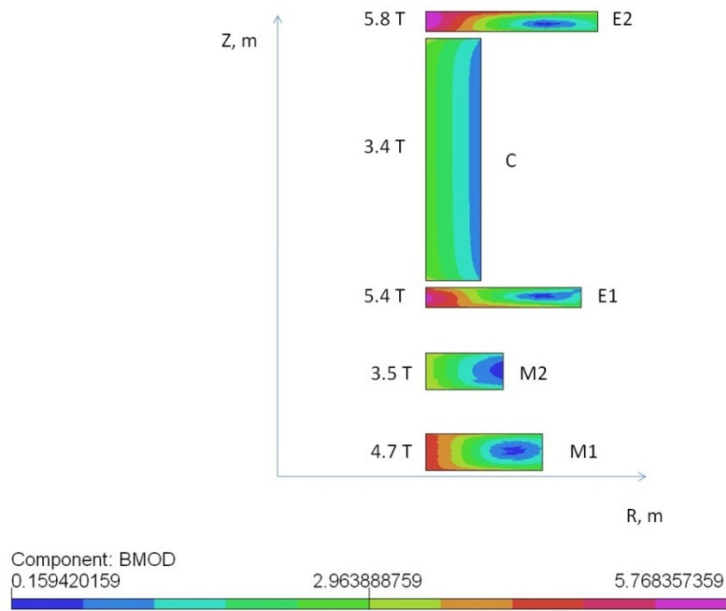


Fig. 4 Model geometry and flux density in the coils.

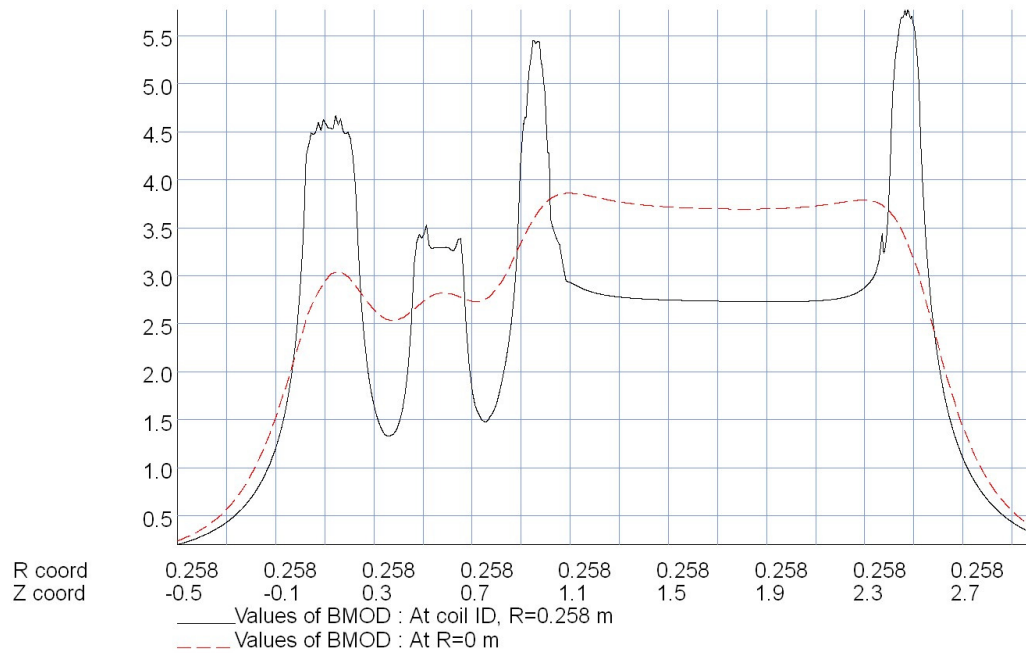


Fig. 5 Flux density distribution in Z – direction for the coil ID and the central axis Z at current 257 A.

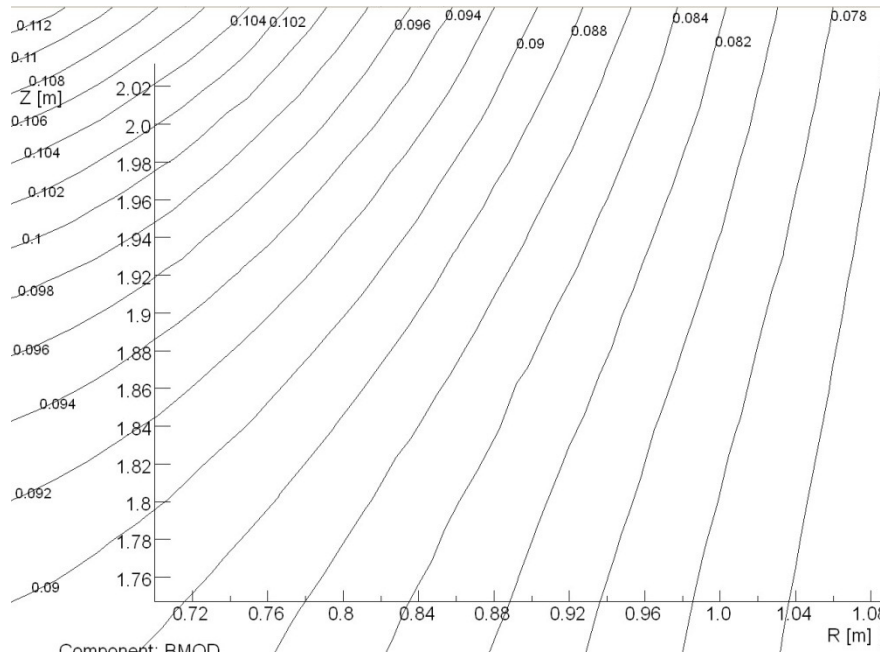


Fig. 6 Flux density Bmod, T in the HTS area at current 257 A.

## 2. HTS Lead Considerations

The steady state magnetic field analysis showed that the calculated peak fields are in agreement with the MICE documentation. Nevertheless, it should be noted that manner in which the current leads were installed does not necessarily result in the position of the leads being fully known after cooldown (See. Fig. 7, Fig. 8).

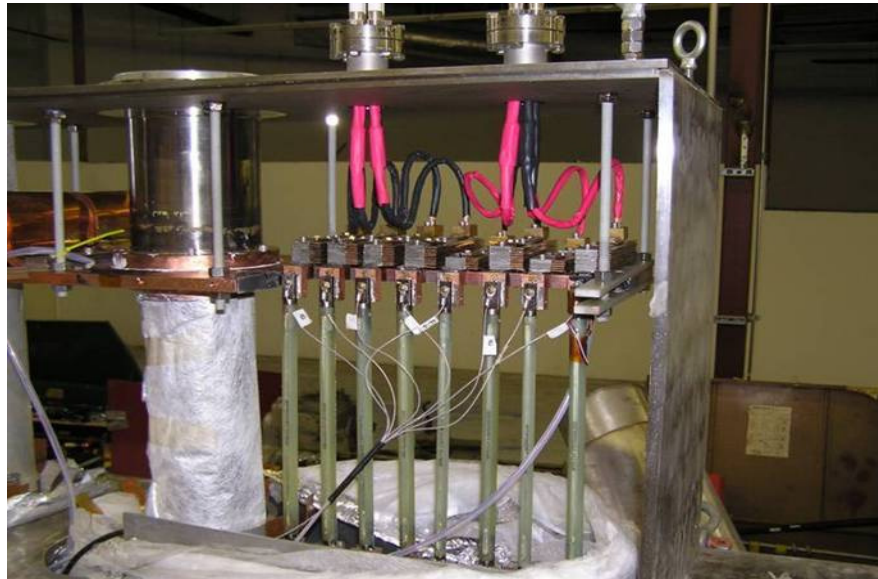


Fig. 7. Upper and HTS leads configuration.

In addition the cold mass axis position was not absolutely fixed during assembly, there is some chance that it could deviate from the outer vacuum vessel axis. Between the two effects, there is some chance the HTS current leads could catch substantial perpendicular field component which will reduce the lead performance (See Fig. 9). This field also could generate circulating currents in the HTS which will additionally heat up these leads during ramping. A more complete analysis and assembly plan should be completed to better understand the position of the leads. If warranted, the addition of a ferromagnetic shield around these current leads will eliminate this effect.

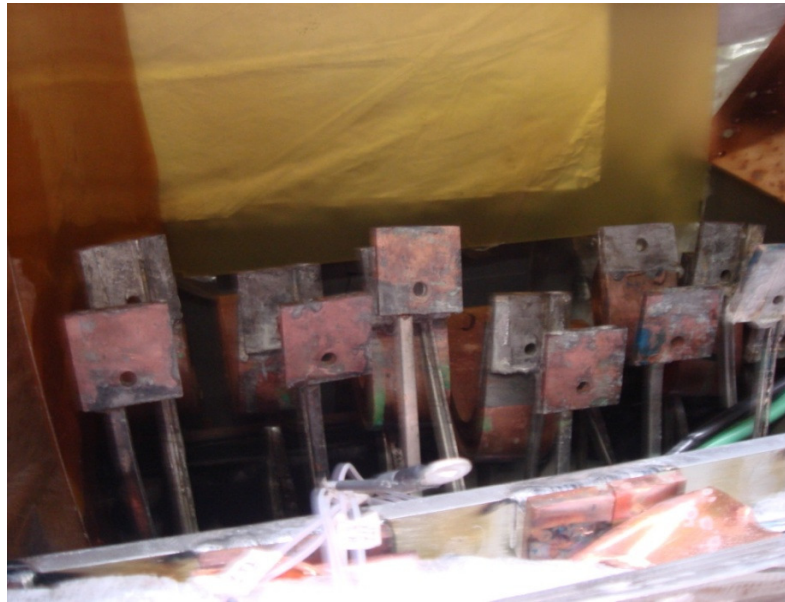


Fig. 8 Flags connected to HTS leads. Leads are removed.

The HTS-110 current lead is capable of carrying, without external magnetic field, 500 A at 65K measured at the warm end.

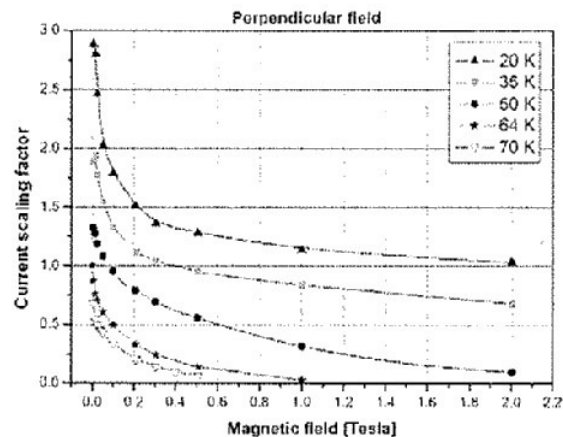
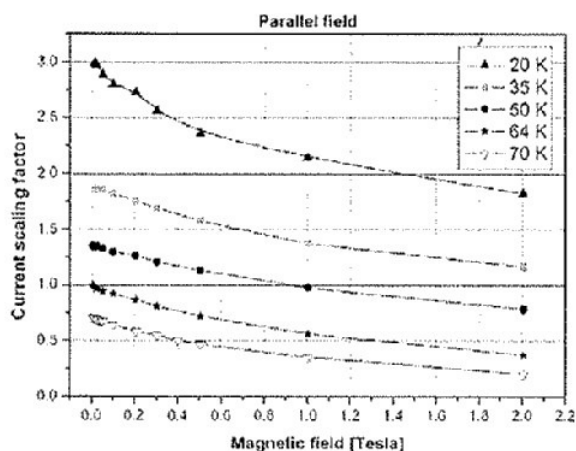




Fig. 9 HTS-110 current factor vs. field and temperature.

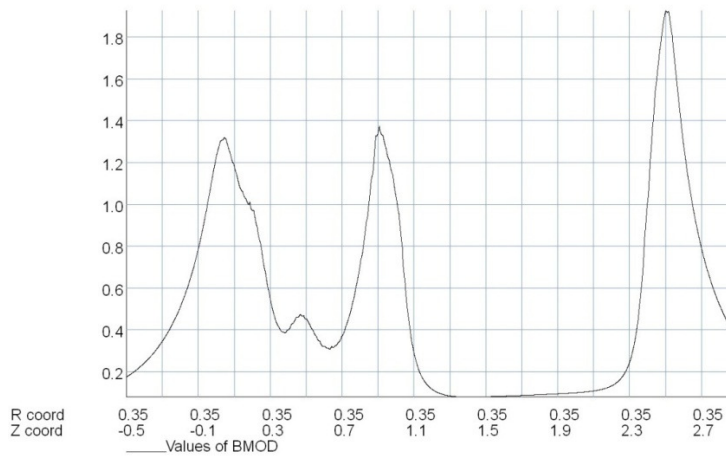


Fig. 10 Flux density on the surface of LHe vessel ( $R=0.35$  m) and in a cold feedthrough areas ( $R=0.35$  m,  $Z \sim 1.8$  m).

### 3. LTS Lead Considerations

Our calculation showed that the field in the cold feedthrough area is less than 0.1 T (See Fig. 10). In this area there should not be any noticeable Lorentz forces and the field influence on the superconductor performance, even without further stabilization, should not be significant (See Fig. 11).

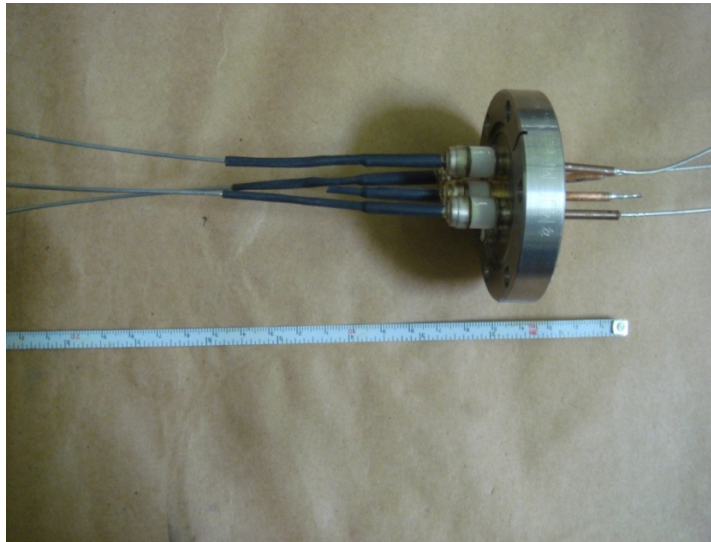


Fig. 11 Cold feedthrough view.

The superconducting wire on right side of the feedthrough was not additionally stabilized because of limited access to this area during assembly. This area may overheat during a quench.

#### 4. Solenoid Magnetic Field Transient Analysis

After fabrication the spectrometer solenoid was trained to achieve the specified operational current of 270 A. All 5 coils of the solenoid were connected in series and powered by the 300 A power supply (See Fig. 3). After the quench at 257 A, the M1 coil showed an open circuit. It is possible the following quench scenario occurred:

- The quench started in the central coil, C, with a current decay  $\sim 5$  s (test info).
- Eddy currents are induced in the coil mandrel.
- In all the other coils there is an induced additional current (in addition to the 257 A positive direction current) in an agreement with the Lentz law.
- The decay time of mandrel eddy currents is defined by the value of the power losses, material heating, heat capacity, and density.
- The decay time in the coils that have not quenched will depend on the value of the shunt resistor (20 m $\Omega$ ).
- There is a “quench back” effect when the heat from the mandrel increases the coil temperatures and transfers them into a normal resistive condition.
- There is a strong coupling between the 5 coils. The coupling is proportional to the self and mutual coil inductances.
- The cold diodes open immediately after the quench.

For the quench modeling, we used the scheme [1] shown in Fig. 3 .

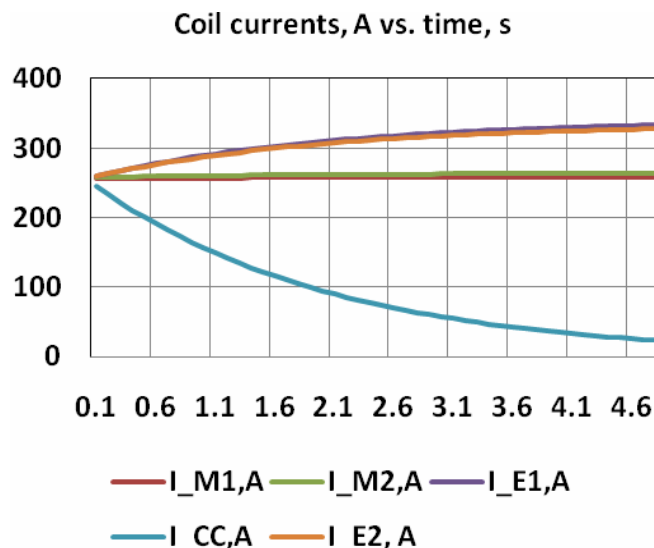


Fig. 12 Coil currents after the quench of the central coil.

One can see that after the quench the current in the central coil decays from 257 A to  $I_{CC} = 20$  A after about 5s. But in all the other coils, the currents increase up to:  $I_{M1} = 258$  A,  $I_{M2} = 264$  A,  $I_{E1} = 334$  A,  $I_{E2} = 328$  A. Even for the M2 coil which has the lowest inductance, the time constant for the current to decay via the 20 m $\Omega$  shunt resistor is 250 s.

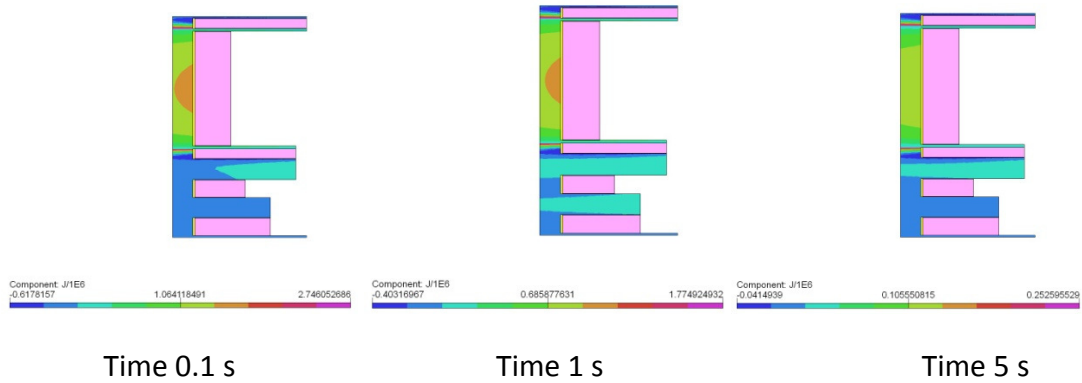


Fig. 13 Aluminum mandrel current density distribution in A/mm<sup>2</sup> vs. time.

One can see in Fig. 13 that the current induced in the mandrel is concentrated under the quenched central coil ( CC ) section of mandrel.

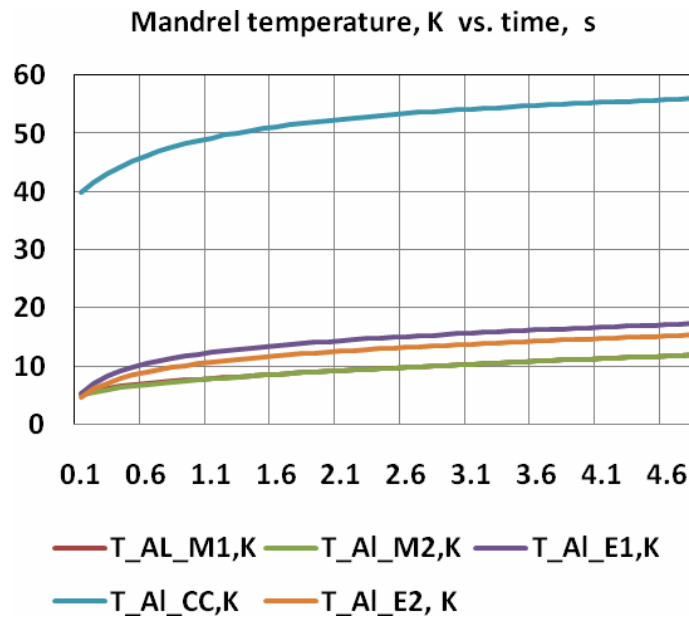


Fig. 14 Aluminum mandrel temperature rise vs. time under the coil centers.



The critical current for the E1 and E2 coils is around 370 A. A quench in these coils which should only occur at fields of 5.4 T and 5.8 T, respectively, ( See Fig. 4) may happened because due to training and thus may occur at lower currents. A coil current of 264 A in the M2 coil corresponds to a field of 3.6 T, which is far away from the critical value of 480 A. Only a “quench back” effect from the aluminum mandrel or coil leads heated by a shunt resistor could transfer the coil M2 into a normal condition. In this situation only a transient thermal analysis can help estimate the time of quench in the M2 coil.

## 5. Solenoid Thermal Transient Analysis

The “quench back” effect due to the aluminum mandrel can be estimated using a solenoid thermal model. The key parameter for this analysis is the thickness of ground insulation between the mandrel outer surface and coil inner surface. In the solenoid documentation it was indicated that the thickness of the ground insulation (G10 + kapton) is 1 mm on the coil inner surface and 3.2 mm on coil sides. This insulation thickness defines the coil temperature rise time and corresponding thermally induced quench time.

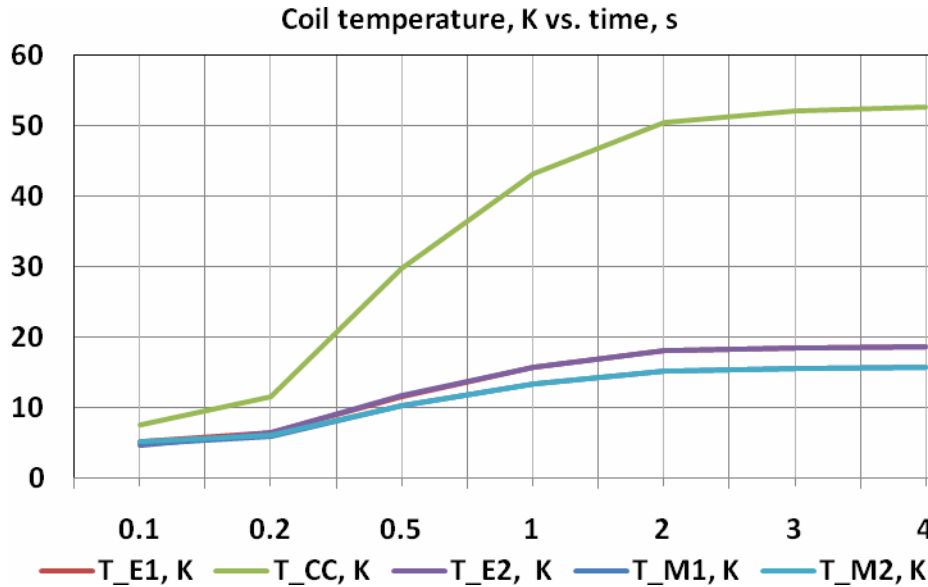


Fig. 15 Coil temperature rise during quench because of mandrel heating.

Because the induced current in the mandrel is concentrated under the quenched central coil CC, the central coil is heated to 50 K after 2 s. This is in an addition to any resistive coil heating. The time of the other coil quenches is the sum of the Al mandrel heating time and the heat transfer from mandrel to the coil. Coils E1 and E2 will be quenched after ~ 1.5 s. Coils M1 and

M2 will see “quench back” effect after  $\sim 2.2$  s. If the real thickness of ground insulation is larger than 1 mm, this delay will be even larger due to the additional thermal resistance of the insulation layer. Fig. 15 shows the coil temperatures at different times. It should be noted that power losses in the mandrel during magnet charging with rate of 0.06 A/s is only 0.065 W and does not produce substantial additional heat load. In [5] these losses were estimated at 0.036 W and the AC superconductor hysteresis losses at 1.01 W during the solenoid charge time 4620 s.

Another dangerous scenario is an E2 coil quench. This coil has the highest peak field and volumetric Lorentz forces, but has a very low coupling with the E1, M1, M2 coils. That is why the “quench back” effect for these (E1, M1, M2 ) coils will be delayed even more than for the first scenario.

## **6. Possible areas for the failure**

The “quench back” effect for the un-quenched coils can be substantially delayed. Coils M1 and M2 will be, from this point of view, in the most dangerous situation. The currents in these coils will circulate until the resistive losses on the 20 m $\Omega$  shunt resistor transfers the leads into the normal condition. The coil leads are heavily stabilized by an extra copper stabilizer and, because of that, have a large temperature margin. The weak areas are the cold feedthrough (See Fig. 11) and the transition area where coil lead copper stabilizer ends and there is only a single strand conductor. A rough estimation shows that the temperature of a single strand will rise with the rate of 300 °C/s. The solder in the feedthrough area will melt at 200 °C after 0.7 s at current 257 A. The strand copper will melt at 1084 °C after 3.6 s. The real scenario will strongly depend on the manufacturing quality, geometry, and exact materials that were used. It is assumed that all coil currents will be short circuited by the cold diodes through the shunt resistors. The delay time for this process is defined by the voltage to open the diodes. In addition some current will continue go through the external HTS current leads because the power supply has low inner resistance. (Note: The power supply was not disconnected during quench.) This current may cause additional HTS lead heating. The value of this current depends on the resistance of the external circuit. If the external circuit resistance is much larger than the 0.1  $\Omega$  - total shunt resistance, than this effect will be low.

## **7. Recommendations**

The above preliminary analysis shows the possibility of a quench initially in one coil will slowly propagation along the Al mandrel, and the timing of the other coil quenches is uncertain. The sequence of coil quenches depends on where the first quench occurs and is related to the

quench current and the field-temperature margin in the other coils. In this situation it seems reasonable to recommend:

- Make a full quench analysis covering the test and operating scenarios. The model must include the real solenoid geometry and material properties;
- Modify the test procedure so all coils are not connected in series for training;
- Consider lower risk solenoid training. For example initially train coils M1 and M2. After that E1, E2, CC with coils M1-M2 powered from a separate power supply at the peak current achieved during training for M1-M2. In this case the M1-M2 circuit will have a small current-field margin and will be quenched almost simultaneously with E1-CC-E2.

At the time of this writing, the solenoid has not been opened up to determine the location of the failure. There seem to be two possibilities:

- If the failure is between the shunt resistor and the feedthrough, Improve the cold feedthrough area and other areas with a single superconductor strand by adding extra copper stabilization;
- If the failure is between the shunt resistor and the coil, the quench protection system should be completely reanalyzed and the modified such that the coils are adequately protected. This could include the introduction of an active quench protection system, or re-optimization of the shunt resistors, for example. Further stabilization of the superconductor strand near the feed through is probably a safe modification in this case as well.
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## **Summary**

The goal of this report is to identify possible issues and ways to improve the magnet system. The preliminary analysis showed a high probability that a quench in one coil will initiate a quench in neighboring coil sections with a relatively long delay time. This may cause overheating in some parts of the leads. A quench monitoring system is needed to understand the total effect caused by “quench back”+ coil mechanical stability + quench propagation velocity. Implementation in the solenoid design of an active protection system may help to resolve some of these issues.

## **References**

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